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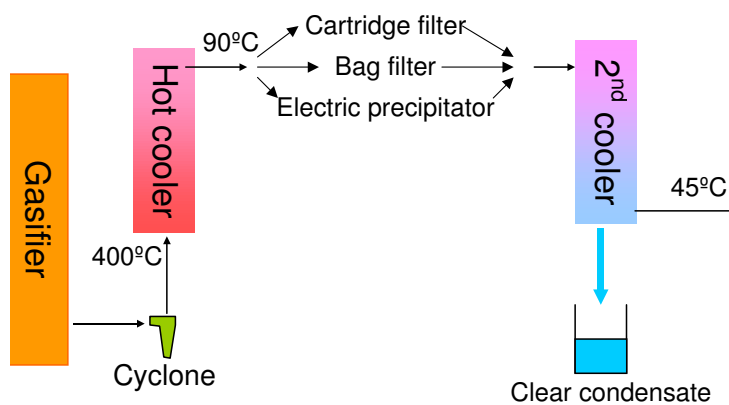
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Low Temperature Particle Filtration of Producer Gas with Low Tar Content

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DTU July 2000



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Abstract

This report describes the tests of different techniques for removing the particulates from producer gas from the 100 kW two-stage down-draft gasifier at DTU¹. The goal of the tests was to identify and implement methods to remove soot particles from producer gas with low tar content. During five days of gasifier operation in November 1999, cartridge filters, bag filters were tested. Attempts to test an electrostatic precipitator failed.

Cold gas cleaning systems using fiber filters (bag filters and filter cartridges at approx. 90°C) were successfully demonstrated with collection efficiencies between 96–99%. A bag filter was successfully operated for 50 hours with automatic cleaning by back-flushes with N₂.

¹The 100 kW gasifier is located at the Department of Energy Engineering, Danish Technical University (DTU). It is based on the two-stage process with separate pyrolysis and gasification. (see e.g. [Henriksen and Nielsen, 1997] and [Bentzen et al., 1999]).

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Chapter 1

Theory

1.1 Particles in producer gas

During the winter 1997–1998, the particles in the gas from the 100 kW gasifier was investigated[Hansen, 1998]. It turned out that the vast majority of the particle mass was soot with diameters of about 0.1–0.5 μm . The tar content was determined to be 10% of the total particulate mass (TPM). Optimizations of the gasifier[Bentzen et al., 1999] were expected to reduce this number further.

Verification of the particle sizes and morphology was done with a scanning electron microscope (SEM). Similar SEM investigations of particles from the counter-flow gasifier in Høgild[Hollensen, 1998] and an open core gasifier[Jacobsen et al., 1994] revealed that soot was also a major part of the particles in the gas from these gasifiers.

1.2 Filtration techniques

To separate particles from a flowing gas, some kind of filter must be used. For a given use, a filter have two important characteristics: its efficiency and its resource-consumption.

The *efficiency* is quantified as the fraction, η , of incoming particles, which are retained by the filter. The efficiency of a filter depends on many parameters, of which the particle size is often the most important. Therefore, the efficiency of a filter is often presented as a graph of η as a function of particle size.

The resource consumption can be divided into initial costs and costs of operation (e.g. pressure drop and use of materials) as well as maintenance costs. The pressure drop often depends on the accumulated amount of particles, and may well define the practical capacity of the filter.

Particle filtration using venturi scrubbers were used to clean the gas in the existing

two-stage installation as well as several other gasification projects. After having recognized the submicron size of the particles, it was obvious to consider other methods for particle removal since scrubbers can not efficiently remove submicron particles. Scrubbers may however have other advantages such as adsorption of some gaseous compounds such as light tars and ammonia.

1.3 Filter media

Filter media are materials, which collect particles from a contaminated gas passing through. Bag-filters, cartridge filters and granular filters belongs to this category. Filter materials may be of the surface collection type (e.g. Gore-TEX and Tetra-TEX membranes) or depth collection type (glass fibers and granular filters).

The particles are collected on the fibers by interception and diffusion. *Interception* is when a particle hits a fiber due to inertia effects or because the particle is large enough to touch the fiber as it passes. Interception is the most important effect for larger particles ($>1 \mu\text{m}$). *Diffusion* is when the Brownian motions of the particle brings it in contact with the filter material. Diffusion is the major collection effect for submicron particles ($<1 \mu\text{m}$).

1.4 Filter efficiency

A theoretical measure for the efficiency of a fiber media is its *single fiber efficiency*, η_s . It is the efficiency of a single, cylindrical fiber. It is assumed, that it is surrounded by a cylindrical gas-filled volume. The volume ratio of fiber and air should correspond to that of the real filter material. The following theoretical equation for η_s was found by Lee and Liu[Liu and Rubow,]. They included an empiric constant, $\varepsilon \approx 1.6$:

$$\eta_s = \underbrace{\frac{2.58}{\varepsilon} \cdot \left(\frac{1-\alpha}{Ku} \right)^{1/3} \cdot Pe^{1/3}}_{\text{diffusion}} + \underbrace{\frac{1}{\varepsilon} \cdot \left(\frac{1-\alpha}{Ku} \right) \cdot \frac{R^2}{1+R}}_{\text{interception}} \quad (1.1)$$

Where

$$R = \frac{D_p}{D_f}$$

and Pe is Pecklets number:

$$\begin{aligned}
Pe &= Pr \cdot Re \\
&= U \cdot \frac{D_f}{a}
\end{aligned} \tag{1.2}$$

Ku is the Kuwabara hydrodynamic factor:

$$Ku = -\frac{\ln(\alpha)}{2} + \alpha - \frac{\alpha^2}{4} \tag{1.3}$$

D_f and D_p are the fiber and particle diameters. The diffusion coefficient, a , can be approximated assuming spherical particles:

$$\begin{aligned}
a &\approx 0.420 v_t \cdot l_{mfp} \\
&= 0.420 \sqrt{\frac{3 \cdot R \cdot T}{M_m}} \cdot \frac{1}{n \cdot A_p} \\
&= 0.420 \sqrt{\frac{3 \cdot R \cdot T}{M_m}} \cdot \frac{1}{n \cdot \frac{\pi \cdot D_p^2}{4}} \\
&= \sqrt{\frac{R \cdot T}{M_m}} \cdot \frac{0.926}{n \cdot D_p^2} \\
&\approx \sqrt{\frac{8.314 \text{ J/(mol} \cdot \text{K)} \cdot T}{22,4 \text{ g/mol}}} \cdot \frac{0.926}{n \cdot D_p^2} \\
&= \sqrt{T} \cdot \frac{0.564}{n \cdot D_p^2}
\end{aligned} \tag{1.4}$$

n is the number of particles per volume. Typical values for R and M_m were inserted above.

Equation 1.1 has been experimentally validated [Lee and Liu, 1982] for $0.034 \mu\text{m} < D_p < 1.3 \mu\text{m}$, $0.01 \text{ m/s} < U < 0.3 \text{ m/s}$, $0.0086 < \alpha < 0.1513$ and $D_f \approx 11 \mu\text{m}$.

The overall filter efficiency, η , can be calculated by the following formula:

$$\eta = 1 - e^{-\eta_s \cdot S} \tag{1.5}$$

where S is the area-factor of the filter:

$$S = \frac{4m_f}{\pi \cdot D_f \cdot \rho_f} \tag{1.6}$$

The plots in Figure 1.1 on the following page shows the single-fiber efficiency as functions of different parameters using eq. 1.1. The following values were used for the plots:

- Fiber packing $\alpha = 0, 1$

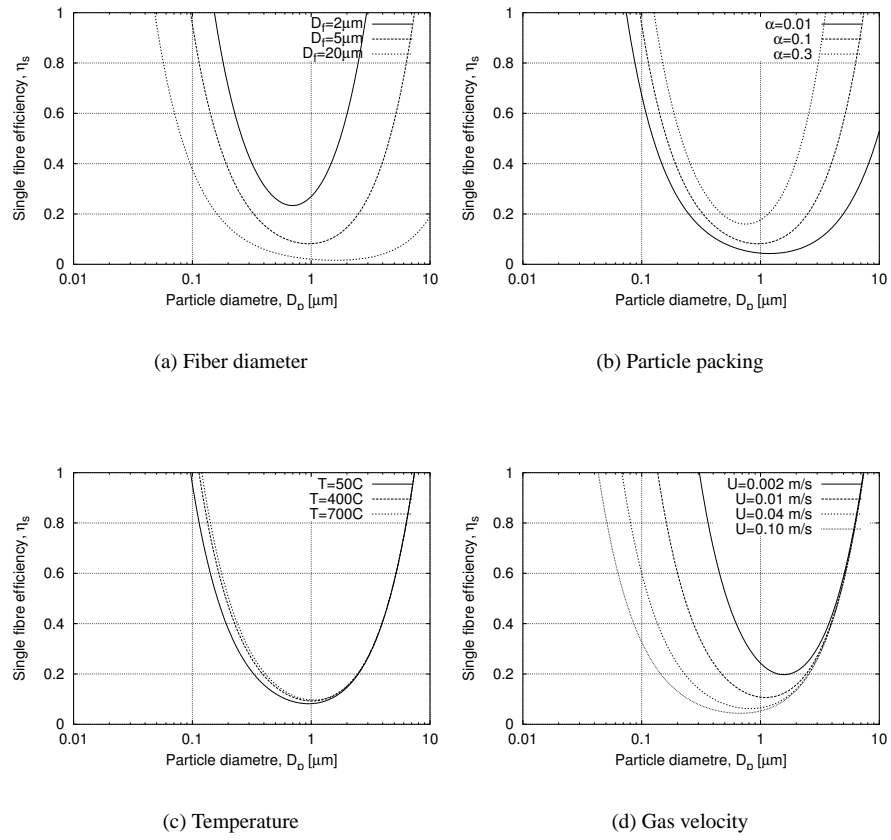


Figure 1.1: Theoretical single-fiber efficiency plots varying different parameters.

- Gas velocity $U=0.02$ m/s
- Gas temperature $T=50^\circ\text{C}=323$ K
- Particle concentration $n=0.03 \mu\text{m}^{-3}$
- Fiber diameter $D_f=5 \mu\text{m}$.

Figure 1.1c shows that the temperature has only negligible impact on η_s (if the gas velocity is kept constant). In contrast, fig. 1.1a indicates that the choice of materials with small fibers (small D_f) markedly increases η_s .

The gas velocity appears to be important for η_s — especially for the smallest particles. This means that a larger area of the filter not only means a lower pressure drop. It also results in a markedly better removal of sub micron particles. The area-specific capacity of the filter is also expected to increase, since a given limiting pressure drop comes with a thicker particle layer on the filter.

The influence of the gas velocity can explain earlier observations, where identical fiber filters had lower removal efficiency when used on particles in a 400 kW gasifier in Års than the 100 kW gasifier at DTU. The particle sizes were similar ($\sim 0.3 \mu\text{m}$). Since the filters had the same area, the gas velocity was about 4 times larger in the 400 kW plant in Års (0.04 m/s opposed to 0.01 m/s), which may explain the difference in removal efficiency.

1.4.1 Practical efficiency measurements

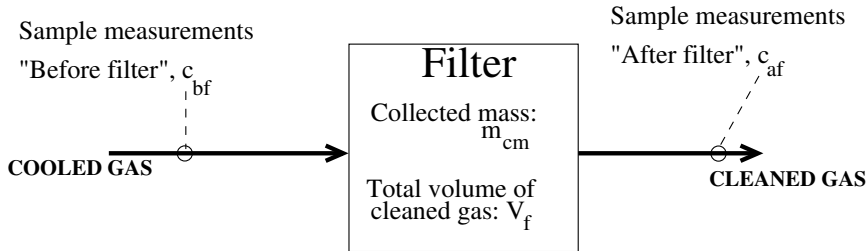


Figure 1.2: Measured values which were used in this work for efficiency determinations of the evaluated filter types.

Figure 1.2 shows a diagram of the measured values, which was used for efficiency determinations of the filters evaluated in this work. From the total collected mass on a filter, m_{cm} , and the total cleaned gas volume, V_f , the average collected particle mass per gas volume, c_{cm} , was calculated:

$$c_{cm} = \frac{m_{cm}}{V_f} \quad (1.7)$$

Isokinetic measurements were made before and after the filter. Since only one sampling equipment was used, these were not measured simultaneously. The filter efficiencies will be estimated in two ways:

The filter efficiency based on the particle measurements before and after the filter:

$$\eta_{bf} = 100\% - \frac{c_{af}}{c_{bf}} \quad (1.8)$$

The filter efficiency based on the particle measurements after the filter and the average collected particle mass, c_{cm} :

$$\eta_{cm} = 100\% - \frac{c_{af}}{c_{cm} + c_{af}} \quad (1.9)$$

For static conditions, η_{bf} and η_{cm} should be equal to the true filter efficiency, η , within the measurement precision. If either the particle load or filtration efficiency varies, both are approximations since no simultaneous determinations of c_{bf} and c_{af} were made.

1.5 Electrostatic precipitators

Electrostatic precipitators do not share the minimum in their efficiency, which characterize fiber filters at about $1 \mu\text{m}$. But they can not efficiently remove larger particles ($>10 \mu\text{m}$).

At the entrance of an electrostatic precipitator, the gas passes the *ionizer*. It contains a strong electric field, often produced by a high voltage thread or spike (typically 12 kV). This field ionizes gas molecules in the gas, which are then attracted to the grounded housing. On their way, the ions collide with the particles in the gas delivering their electric charge. Each particle will receive charges from several ions this way until it reaches the *saturation charge*, where the ions are repelled.

After the ionizer, the gas passes the *collector plates*, which are charged (typically 6 kV). Between each collector plate an electrically grounded plate produces a strong electrical field. This field forces the particles to the collector plates, where it adheres to their surface. This adherence can sometimes be improved with a layer of oil or similar liquids.

Chapter 2

Experimental Work

This chapter describes experimental preparations and tests made with gas from the 100 kW two-stage gasifier at DTU in November 1999.

2.1 Design of new gas cleaning system

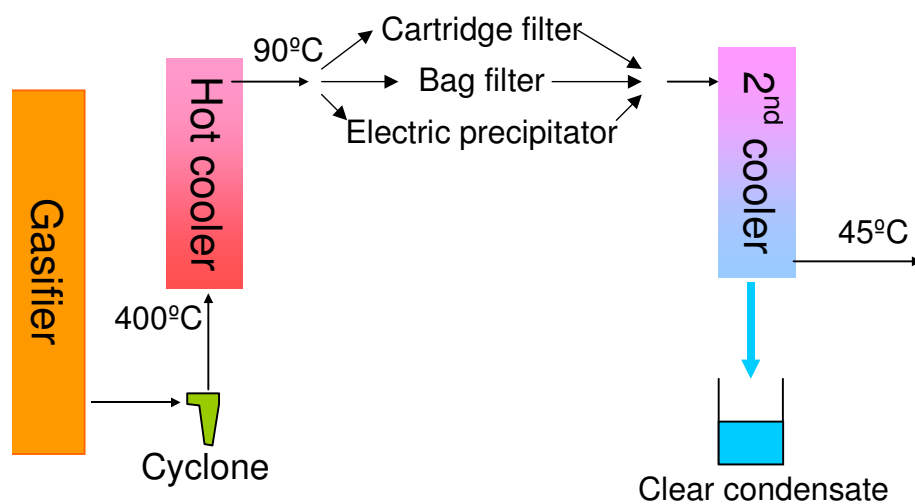


Figure 2.1: Schematic of the new cleaning system November 1999.

Figure A.1 on page 26 shows a schematic diagram of the 100 kW gasifier prepared

for the gas cleaning tests. The *water dew point* of the gas was 60–67 °C¹. It was necessary for the filtration to avoid the presence of liquid, condensed water in the gas. Water could cause fiber filters to block and the electrostatic precipitator to short circuit. In order to be able to control the temperature of the gas in the filter, the gas passed a thermostated cooler before the filter.

The tested electrostatic precipitator, a SMOG-HOG SH-10, required a much higher flow rate (500–1700 m³/h) than the available gas flow (70 m³/h). A loop driven by a blower was added to increase the flow rate during tests with the electrostatic precipitator. The filter was built for ventilation purposes, so it was necessary to tighten the filter with silicon glue in order to make it gas-tight. The filter was insulated to keep the surfaces above the dew point of the gas.

	Envi EN-13	Envi EN-247	Envi EN-712	MANN C23 440/1
Material	Tetratex	Impregn.	Cellulose	4MFN
	on polyester	paper	polyester	paper
Fiber diameter	Membrane			37–50 µm
<i>U</i> given $\Delta p=20$ mmWG	0.083 m/s	0.12 m/s	0.22 m/s	
$\Delta p=10$ mmWG				0.075 m/s
Mass	200 g/m ²	190 g/m ²	130 g/m ²	
Area	2.0 m ²	4.5 m ²	4.5 m ²	1.7 m ²
Absolute permeability	600 m ³ /h	1930 m ³ /h	3600 m ³ /h	460 m ³ /h
given Δp:	20 mmWG	20 mmWG	20 mmWG	10 mmWG
Packing density, α				>18 %

Table 2.1: Data for cartridge filters from data sheets. The filter areas were measured on the actual filters. *U* is the expected gas velocity of atmospheric air through a clean filter at the given a pressure drop Δp .

Five different cartridge filters were tested during the experiment. Their data are shown in table 2.1. Two different bag filter types were tested (Table 2.2). Polyester bag filters are commonly used due to its low price. It can operate up to 150 °C, which is higher than e.g. the tested Dralon-T type.

2.2 Experimental conditions

2.2.1 Gasification modes

The experimental work was carried out from November 21. to 26. 1999. During the test period, the gasifier operated in three different modes:

Normal gasification “Normal” operation of the gasification plant.

¹The water dew points were estimated from the input fuel and added steam and continious measurements of the contents of H₂, CH₄, CO and CO₂ in the gas.

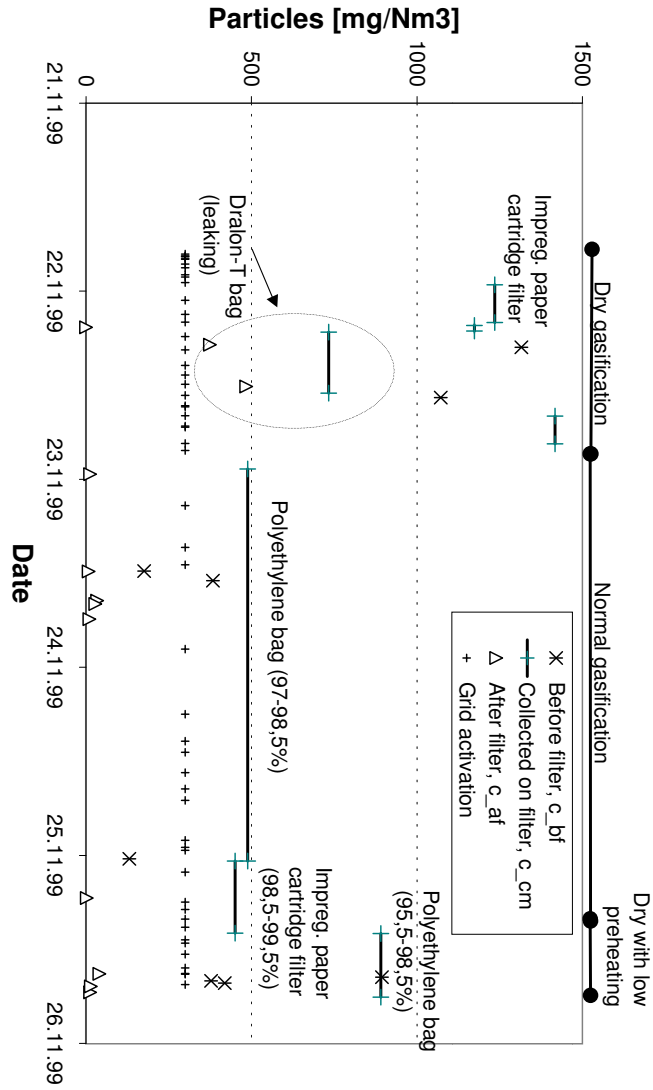


Figure 2.2: Particle load determinations. “Collected on filter” is c_{cm} from equation 1.9. The approximate particle collection efficiencies during the tests are shown in parenthesis (the values are shown in table 2.4).

	DT/DT 501	PE/PE 501
Material	Dralon-T	Polyester
<i>U</i> given:	$\Delta p=20$ mmWG	0.33 m/s
	$\Delta p=82$ mmWG	1.22 m/s
Mass	500 g/m ²	500 g/m ²
Area	0.92 m ²	0.92 m ²
Thickness	2.3 mm	1.8 mm
Density	0.22 g/cm ³	0.28 g/cm ³
Max. temperature	120 °C	150 °C
Hydrolysis resistance	Good	Bad
Packing density, α	19 %	20 %

Table 2.2: Data for bag filters from data sheets.

Dry gasification No steam was added to the gasification chamber and the fuel (wood chips) were very dry. It was expected to give a better overall energy efficiency of the plant as well as a higher soot production.

Dry with low pre-heating The temperature in the pyrolysis unit was lowered. It was expected to cause higher tar-production.

Figure 2.2 on the page before shows the particle load determinations during the full experiment ordered by time. The particle loads in the raw gas, before the filter (bag or cartridge) and after filter were measured by an isokinetic sample system conforming to VDI2066[VDI, 1975]. These samples took 5–10 minutes. The average amount of particles collected by each cartridge and bag filter are represented by the horizontal lines covering their operation times.

2.2.2 Grid activations

In the top of figure 2.2 it is shown that the gasifier was initially operated in the dry gasification mode. As expected, the soot production was higher than during normal gasification. Unfortunately, this seemed to cause problems with the gas permeability of the coke bed resulting in unexpectedly high pressure drops across it. The normal procedure to restore the bed pressure drop is to “activate” the grid under the coke bed. The grid supporting the bed is manufactured so that it is possible to rotate its parts. When this was done, the openings in the grid were expanded so that small amounts of bed material could pass through the grid. Normally it would not be necessary to activate the grid at all but during the November test the pressure drop was a serious problem — possibly due to the excess amounts of soot produced during dry gasification. It was thus needed to activate the grid about 50 times during the November test.

During grid activations, the particle load in the gas increases dramatically. In fact a cartridge filter in service during repeated grid activations during the November test

received an average particle load exceeding 6500 mg/Nm^3 . Since such extreme variations in particle load may have an impact on the performance of the filter in service, the times of “grid activations” will be noted when evaluating the filters. On the time-pressure graphs (see e.g. figure B.3 on page 30), small crosses mark times of grid activation.

2.3 Cartridge filters



Figure 2.3: EN-712 cartridge filter after operation during dry gasification.

Figure B.1 on page 28 shows the pressure drops across the tested cartridge filters during their operation. The curves are annotated with the material, filter type number (see table 2.1 on page 10), filter areas and masses of collected particles per cubic meter. The collected particle masses were calculated from the mass increase of the filters during operation. Where isokinetic dust samples were taken after the filters (two occasions), their results are shown in square boxes. Both of the dust samples showed marginal dust concentrations after the filter proving very good cleaning efficiencies of $\eta > 98 \%$ (see details in table 2.4 on page 18). This means that the collected particle masses shown in figure B.1 are good approximations to the average particle concentrations before the filter.

The filters were assumed to be saturated with particles when their pressure drops reached unacceptable values (400–500 mmWG). The graphs show clearly that the pressure drops increased exponentially so acceptance of larger pressure drops would only result in small increases in operation time. The operation times of the filters were

relatively short — less than four hours during dry gasification ($\approx 1200 \text{ mg/Nm}^3$ particles) and less than 8 hours during dry gasification with low pre-heating ($\approx 450 \text{ mg/Nm}^3$ particles). Such short operation times would be unacceptable for long-term continuous operation without some sort of automatic filter change or regeneration.

The cartridge filters appeared to work effectively until they were saturated with particles. The measured efficiencies of the filters exceeded 98 % (see the numbers table 2.4 on page 18). The cartridges were replaced by a simple two-minute operation, which was easy but required the filter to be cut off from the gas stream. The cartridge filters are very compact and seemed to be a good choice for efficiently filtering gas streams with small particle contents or short operation times. For example, it would be good as a “police filter” after other gas cleaning components in order to ensure particle-free gas even if the main gas cleaning systems should fail.

2.4 Bag filters

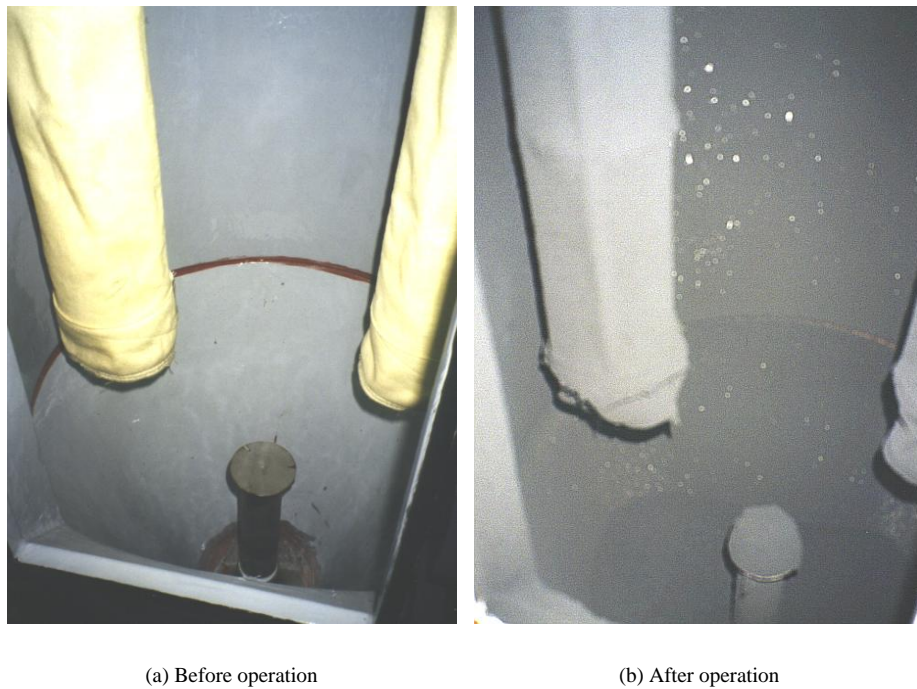


Figure 2.4: Mounted Dralon-T bag filters seen through the access door.

For each of the three bag filter materials, a setup with two bags (1 meter, 0.46 m^2 each) were tested. The total filter area was 0.92 m^2 corresponding to an average gas velocity of $U=0.02 \text{ m/s}$. The bag filters were tested with cleaning pulses of 50 ms with

N₂ from a pressurized tank with 3.5 bar gauge.

During the dry gasification, Dralon-T bags were tested. Unfortunately, the filter leaked due to incorrect assembly. The filtration efficiency of the leaking filter was measured to 50–70 %, which means that the real efficiency of the filter lies somewhere above this value.

From figure 2.2 it can be seen that during the test period for this filter (23.11.99–25.11.99) the particle loads measured by samples “Before filter” was lower than the value calculated based on the collected particle mass (“Collected on filter”). A possible explanation is the increase in particle load the grid was activated (see section 2.2.2). No isokinetic samples were taken during grid activations, but the filters in operation received the full particle load.

Figure B.3a on page 30 shows the pressure drop across the PE filter bags during the first ten hours of their service. Externally caused interruptions are marked with a circle on the time axis. During such interruptions, the plant was automatically set in “restart mode” where the gas was rerouted to a flare so that the filter was put off-line. The interruptions took from two minutes to a few hours. Off-line periods were removed from the graphs. Circles on the time axis marks the off-line periods. The bags appeared to clog up due to condensing water. This was caused by failure to adjust the gas temperature above the increased dew point of the gas as the plant switched from dry to normal gasification.

The gas temperature was increased from 70 to 90 °C and the next ten hours of service are shown in figure B.3b. The filter seemed to successfully restore an acceptable pressure drop with cleaning pulses. Measurements of the particle load in the gas after the PE bags (see the boxes on figure B.3b) showed particle loads below 40 mg/Nm³. The highest value (39.9 mg/Nm³) was the only measurement that included a cleaning pulse of the bag filter. This indicates that the particle load peaks during back flushes. According to the manufacturer of the filter, this effect is likely to decrease if the blow pressure is decreased from 3.5 bar to 1.5–2 bar.

Gasification mode	Bag type	Particles [mg/Nm ³]	Backflush period [min]	Graph
Dry	Dralon-T	1200	3.6	Figure B.2
Normal	PE/PE 501	450	60	Figure B.3b
Low pre-heat	PE/PE 501	900	15	

Table 2.3: Bag filter test data. See data sheets for the bags in table 2.2.

Table 2.3 shows a summary of average backflush periods observed during the bag filter tests. As noted, backflushes occurred automatically when the pressure drop across the bag filter exceeded 300 mmWG. As expected, the backflush periods decreased for increasing particle loads. The backflush periods are expected to increase if larger filter

areas (e.g. more bags) are chosen.

The tests with bag filters showed that bag filters can very effectively remove the particles from producer gas. Particle removal efficiencies were generally measured found 96–99 % (see table 2.4). Backflush blow cleaning was successfully demonstrated during a 50 hours test without signs of filter blockage.

2.5 Electrostatic precipitator

The attempts to operate the SH-10 electrostatic precipitator on the producer gas did not succeed. An indicator lamp on the precipitator was supposed to be lit when the filter was operational (ionizer and collector plates were fully charged without short circuits). At no time was this indicator lit when producer gas passed the precipitator. The following is a description of the preparations and operations in the attempt to make it work.

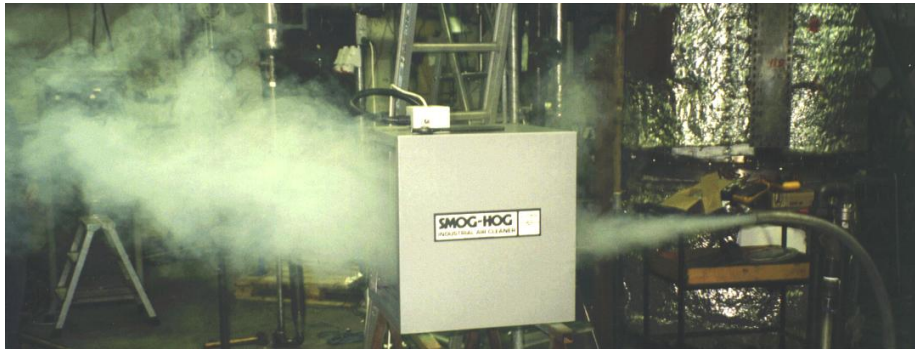
A pre-test of the precipitator prior to connecting it to the producer gas, confirmed that the filter did operate in atmospheric air. It was easily seen that smoke from a smoke gun was removed when the filter was turned on. (Figure 2.5 on the facing page).

To avoid explosive air/gas mixtures in the precipitator, it was filled with N₂ gas before the producer gas was led through it. Since the precipitator was insulated but not pre-heated, water in the gas would initially condense inside the precipitator. If this was a problem, it was assumed that it would only be temporary, since the hot gas would heat up the filter to the point where it was well above the dew point (of $\approx 67^{\circ}\text{C}$) and dry. The exit temperature of the gas was measured in order to confirm this.

After 75 minutes of operation with an entrance temperature of the gas exceeding 90°C , the exit temperature had stabilized above 80°C . But the filter had at no point been operational. Then the filter was disconnected, filled with N₂ in order to avoid explosion hazards and opened. No signs of wet spots were visible, thus it appeared that the filter had been dry during the test.

After the test, we worked with the supplier² of the precipitator to find an explanation for the failure to make the filter operate on the gas. One possibility mentioned was the lack of oxygen in the gas. Some precipitator designs rely on polar gases, which can slow down the charged electrons. Otherwise, the electric current would be too high from the ionizer to the cabinet of the precipitator. For most applications, precipitators can rely on the presence of O₂ for this, but oxygen is absent producer gas. To confirm this effect, the filter was filled completely with N₂. It was expected, that it would fail to operate, but it was functional (according to the lit indicator). The lack of oxygen did not seem to be an explanation for the malfunction.

²Miljøvent I/S, Portlandsvej 27, DK-2300 Copenhagen.



(a) Turned off



(b) Turned on

Figure 2.5: Pre-test of precipitator with filter off and on.

2.6 Filter efficiencies

Filter type	Gasification mode	Gas velocity U [m/s]	Before filter	Collected average	After filter	Efficiency	
			c_{bf} [mg/Nm ³]	c_{cm} [mg/Nm ³]	c_{af} [mg/Nm ³]	η_{bf} [%]	η_{cm} [%]
Dralon-T [†]	Dry	0.021	1315	733	375 [†]		
Dralon-T [†]	Dry	0.021	1072	733	485 [†]		
PE/PE-501	Normal	0.021	384	489	7.5	98.0 %	98.5 %
PE/PE-501	Normal	0.021	384	489	34.0 [‡]	91.1 %	93.5 %
PE/PE-501	Normal	0.021	384	489	27.6	92.8 %	94.7 %
PE/PE-501	Normal	0.021	384	489	10.4	97.3 %	97.9 %
PE/PE-501	Low pre-heat	0.021	894	890	39.9 [‡]	95.5 %	95.7 %
PE/PE-501	Low pre-heat	0.021	398	890	13.6	96.6 %	98.5 %
Cartr. EN-13	Dry	0.010		1173	<1		100.0 %
Cartr. EN-247	Normal	0.004	131	451	2.1	98.4 %	99.5 %

Table 2.4: Filter efficiencies. See section 1.4.1 for calculations.

[†]The bag filter leaked gas around the Dralon-T filter due to faulty montage.

[‡]During these measurements the bag filter back-flushed, apparently increasing the particle load after the filter.

Table 2.4 shows the results of particle measurements in the gas before and after the filter as well as the average collected particle mass on the filters, c_{cm} (see eq. 1.7). No particle measurements were made simultaneously, so each measurement after the filter was compared to the most recent measurement before the filter. Thus the same measurement of c_{bf} appears several times in the table. The last column shows the calculated collection efficiencies using the formulas for η_{bf} and η_{cm} in section 1.4.1.

c_{bf} were generally lower than c_{cm} since the dust-releasing grid activations were avoided during all particle measurements in order to get consistent measurements.

If the measurements of c_{af} taken during a back-flush blow of the bag filter are ignored, most measured efficiencies of the PE/PE-501 bags were between 96.6–98.5 %. A single measurement of c_{af} exceeded 27 mg/Nm³. It has not been possible to explain why this measurement showed more than the double particle load than the other measurements.

The measured efficiencies of the cartridge filters (the two last rows in table 2.4) shows excellent collection efficiencies. It should be noted that the gas velocities, U , through the cartridge filters were much lower than through the bag filters. As shown in section 1.4, the collection efficiency, η , is expected to increase with decreasing U .

2.7 Analysis of particles

More than two kilograms of particles were collected during the test in the filters. They were examined by chemical extraction, pyrolysis, combustion, scanning electron mi-

croscopy and ESD atom analysis.

2.7.1 Tar content

The tar content in the particle samples were determined by:

- pyrolyzing samples at 600°C.
- extracting samples with acetone.

Earlier evaluations of tar determination methods[Hindsgaul et al., 2000] proved that tar determinations by pyrolysis resulted in higher values than by extraction with acetone, dichloromethane or anisole.

Figure 2.6 on the following page shows a summary of the tar determinations made during the test of November 1999. The x -axis is the time of determination. The “pyrolyzable” and “acetone solubles” are calculated from the determined particle tar mass and the gas volume, which had passed through the filters during operation. These determinations are averages over the full operation times of each filter, shown as vertical lines reaching across the time-span of filter operation. DTI³ performed tar measurements of 1–2 hours durations. These were made on gas sampled at the gasifier outlet (“raw gas”) and after the particle filters (“clean gas”).

Since the tar found in the particles had been taken from the gas stream, it was expected that the tar level in the gas would be reduced with — at least — the amount found in the particles. If one compares the tar reduction from “raw gas” to “clean gas” with the tar found in the particles on figure 2.6, it seems like *more* tar was collected in the particles, than removed from the gas. Since there are no tar sources in the cleaning system, this can not be true. Several reasons for these measurements exist:

- The tar determination methods were different. As noted, the pyrolysis method gives higher values than extraction methods.
- Grid activations were avoided during the DTI measurements in order to get reproducible results. Since the grid activations resulted in great momentary increases in particle levels, additional tar reached the filters with these particles. This would increase the tar averages determined from the particles collected by the filters.

2.7.2 Ash

The ash contents in the particles were determined by combustion. The samples were heated to 550 °C in atmospheric air and the residual mass was assumed to be ash. Up to 35 % of the particle mass collected in the bag filter was identified as ash this way.

³Danish Technological Institute <http://www.teknologisk.dk/>

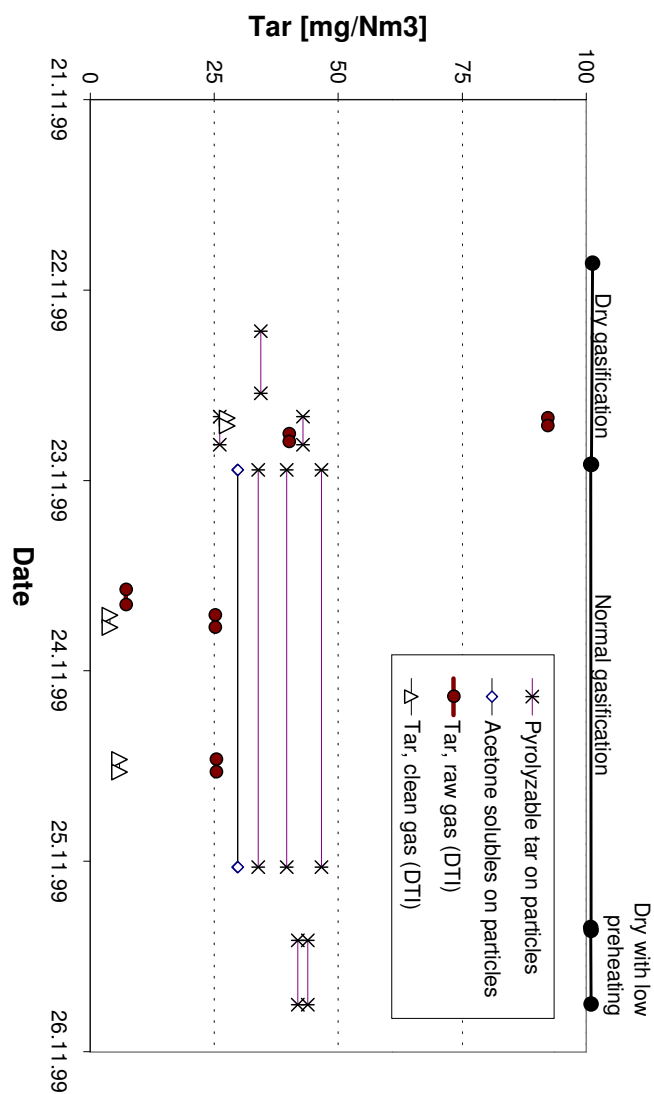


Figure 2.6: Tar determinations in the gas measured by particle and gas samples. Some of the pyrolysis determinations were repeated on particle samples from the same filter. They appear above each other in the figure and indicate a low precision of the pyrolysis determinations.

This corresponds to 150–200 mg/Nm³ ash collected from the gas. This was surprising since particles collected during earlier tests in 1998[Hansen, 1998] appeared to have an ash content below 3 % (mass).

Scanning electron microscopy (SEM) with an ESD detector was used to determine the geometrical distribution of the ash in the particles. The ash appeared to be a dilute part of the particles. This contrasts investigations of two-stage gasifier soot in 1998, which showed that much (possibly all) of the ash content appeared as single ash particles of sizes up to 3–4 μm . No ash particles were observed in the present samples from November 1999. This may be due to the higher temperatures reached in the gasification chamber during the dry gasification mode in the 1999 test, where some ash compounds could reach non-solid phases.

Conclusion

Two dry, cold particle removing component types were successfully tested on cooled producer gas from the two-stage gasifier at DTU: Bag filters and four different cartridge filters. Attempts to operate an electrostatic precipitator failed.

It was demonstrated that the bag and cartridge filters had very good cleaning efficiencies (96–99 % mass). It was shown theoretically that larger filter areas could further improve the collection efficiencies of such filters for submicron particles such as those found in the producer gas. Optimizing the choice of filter material may also improve collection efficiencies. Summarized, bag and cartridge filters are effective for particle removal from producer gas with low tar content.

Backflush cleaning of the bag-filters with N₂-pulses were successfully demonstrated for 50 hours cleaning producer gas.

Symbols

a Diffusion coefficient (eq. 1.4)

c Particle load. [mg/Nm³]

c_{af} Measured particle load after filter. [mg/Nm³].

c_{bf} Measured particle load before filter. [mg/Nm³].

c_{cm} Collected particle mass per total gas volume. [mg/Nm³] (eq. 1.9).

C Cunninghams surface friction factor ($C \approx 1$ in qualitative analysis)

D_p The particle size/diameter [m]

D_f The fiber diameter [m]

Ku Kuwabena hydrodynamic factor (eq. 1.3)

l_{mfp} Mean free path.

m_{cm} Total particle mass collected by filter. Determined by difference weighing.

m_f Mass of filter (eq. 1.6).

M_m Mole mass.

n Number of particles per volume.

Δp Pressure drop at filter.

Pe Pecklets number (eq. 1.2)

S Area factor of filter material (eq. 1.6)

T Temperature.

U Gas velocity (mean velocity through filter material without material).

V_f Total gas volume that passed through filter during operation. [Nm³]

α Packing density of filter material

ε Empiric factor $\varepsilon \approx 1,6$ (eq. 1.1).

η Filter collection efficiency. (Collected particulate mass divided by particulate mass before filter).

η_{bf} Filter collection efficiency estimate based on particle measurements c_{bf} and c_{af} . (eq. 1.8).

η_{cm} Filter collection efficiency estimate based on the particle measurements c_{cm} and c_{af} . (eq. 1.9).

η_s Single fiber efficiency (see section 1.4).

ρ_f Density of filter fibers [g/m³].

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Gasifier layout

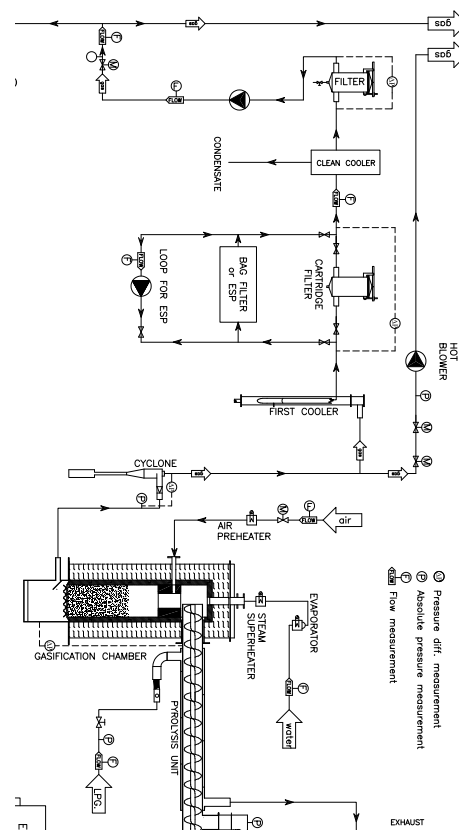
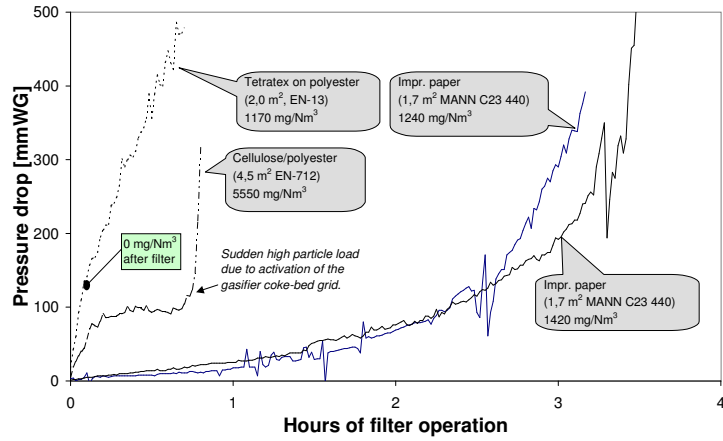


Figure A.1: Schematic of the DTU 100 kW gasifier during the test in November 1999.

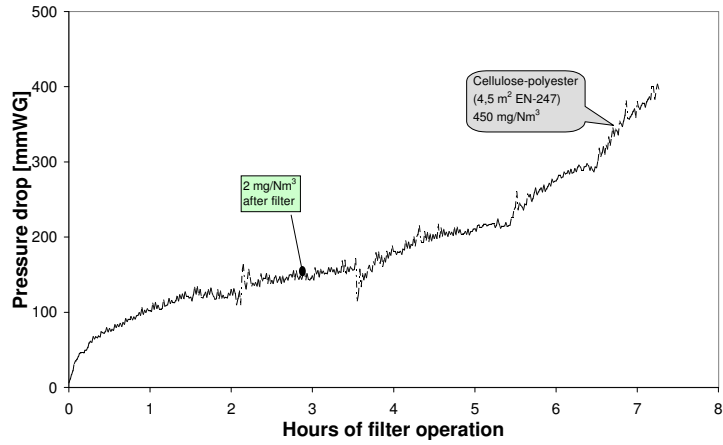
Appendix B

Time-pressure diagrams

This appendix shows diagrams of the pressure drops across the tested filters during the tests.



(a) Dry gasification



(b) Dry gasification with low preheating

Figure B.1: Cartridge filter pressure drops as a function of service time. See section 2.3 on page 13.

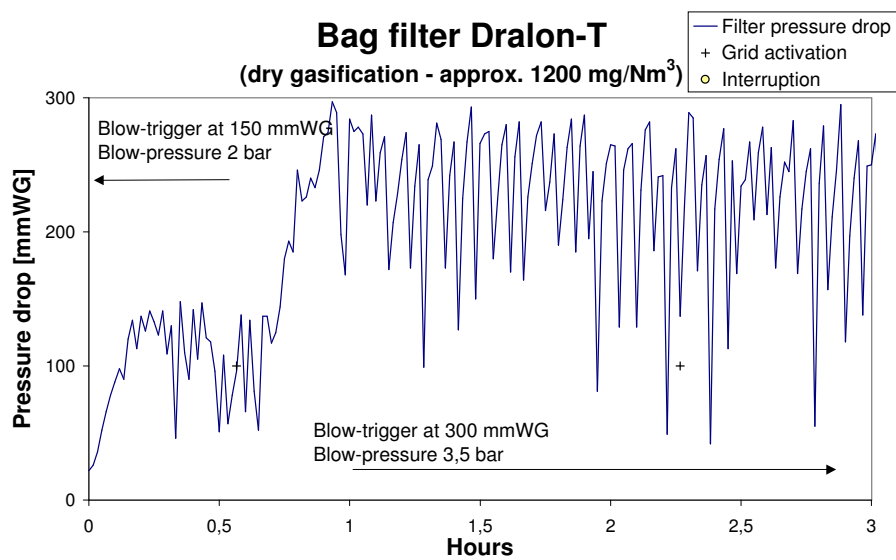
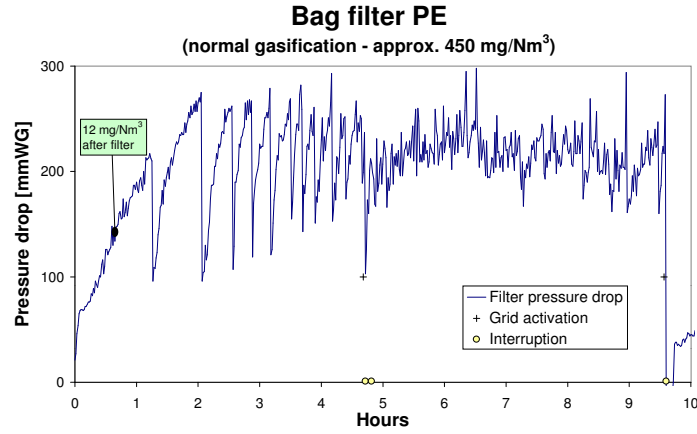
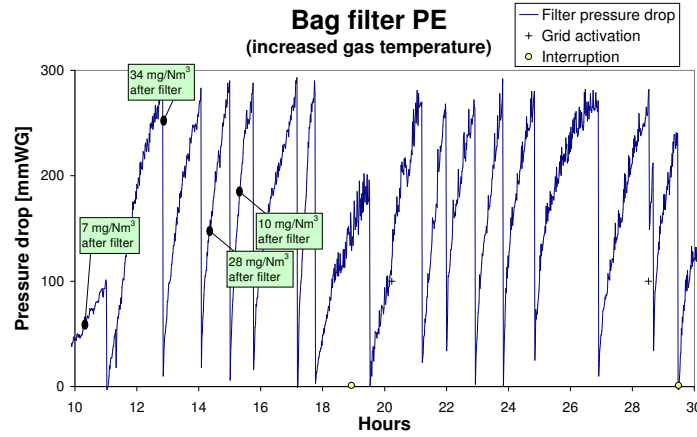


Figure B.2: Bag filter operation with DT/DT 501 under high particle load. During the second hour, cleaning pulses occurred every 3.5 minutes. See section 2.4 on page 14.



(a) Gas temperature below dew point



(b) Gas temperature above dew point

Figure B.3: PE/PE 501 bag filter pressure drop during normal gasification (~ 450 mg/Nm³). See section 2.4 on page 14.